First Observation of Vector Boson Pairs in a Hadronic Final State at the Tevatron Collider

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First Observation of Vector Boson Pairs in a Hadronic Final State at the Tevatron Collider

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We present the first observation in hadronic collisions of the electroweak production of vector boson pairs (WW, WZ, or ZZ) in p̅p collisions has been observed in the fully leptonic final states at the Fermilab Tevatron collider[1,2]. Diboson production has not yet been conclusively observed in p̅p collisions in decay channels involving hadrons [3]; however, evidence for diboson decays into an lνq̅q̅(0) final state (l = e, µ, τ; q = u, d, s, c, b) has been recently presented by the D0 collaboration [4].

Measurements of diboson production cross sections provide tests of the self-interactions of the gauge bosons. Deviations from the standard model (SM) prediction for the production rates could indicate new physics [5,6]. Furthermore, given that diboson production is topologically similar to associated Higgs boson production, p̅p → VH + X (V = W, Z), the analysis techniques described in this Letter are important for Higgs boson searches.

Here, we present the first observation at a hadron collider of diboson production with one boson decaying into leptons and the other into hadrons. The production of heavy gauge boson pairs (WW, WZ, or ZZ) in p̅p collisions has been observed in the fully leptonic final states at the Fermilab Tevatron. We observe 1516 ± 239(stat) ± 144(syst) diboson candidate events and measure a cross section α(p̅p → VV + X) of 18.0 ± 2.8(stat) ± 2.4(syst) ± 1.1(lumi) pb, in agreement with the expectations of the standard model.

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The production of heavy gauge boson pairs (WW, WZ, or ZZ) in p̅p collisions has been observed in the fully leptonic final states at the Fermilab Tevatron. The data correspond to 3.5 fb⁻¹ of integrated luminosity of p̅p collisions at √s = 1.96 TeV collected by the CDF II detector at the Fermilab Tevatron. We observe 1516 ± 239(stat) ± 144(syst) diboson candidate events and measure a cross section α(p̅p → VV + X) of 18.0 ± 2.8(stat) ± 2.4(syst) ± 1.1(lumi) pb, in agreement with the expectations of the standard model.
be less than 90\% to ensure that electrons and photons are not counted as jets.

In order to suppress the MJB, we use a $E_T$ resolution model to distinguish true $E_T$ originating from undetected neutrinos from fake $E_T$ due to jets that are not measured accurately. The $E_T$ significance is a dimensionless quantity based on the energy resolution of the jets, on soft unclustered particles, and on the event topology. The $E_T$ significance is typically low when $E_T$ arises from mismeasurement. In addition to having a small significance, the $E_T$ will often be aligned with a jet. We select events with $E_T$ significance larger than 4 and azimuthal angle between $E_T$ and the nearest jet ($\Delta \phi(E_T, \text{jet})$) greater than 0.4 radians.

Finally, we apply several requirements that suppress contamination due to cosmic-ray, beam-related, and other noncollision backgrounds. Events are required to have at least one reconstructed vertex formed by charged particle tracks. The transverse energies of all calorimeter towers are calculated with respect to the z position of the primary vertex with the largest $\sum p_T$ of associated tracks. The electromagnetic fraction of the total event energy has to be larger than 30\% in order to reduce beam-related backgrounds. The arrival time of both leading jets as measured by the electromagnetic shower timing system [13] has to be consistent with the $pp$ collision time. The remaining noncollision background has a smooth $M_{jj}$ distribution and accounts for less than 0.2\% of the final number of selected events. After all cuts were applied, we find 44,910 events in the final sample.

The shape and normalization of the MJB are determined from the data. A vector, $\mathbf{p}_T$, analogous to the calorimeter-based $E_T$, is constructed from the vector sum of the transverse momenta of particles measured in the tracking system, and is largely uncorrelated to $E_T$ for events where jets are not reconstructed accurately. In the absence of $E_T$ arising from mismeasurement in the calorimeter, the $\mathbf{p}_T$ and $\mathbf{E}_T$ will be aligned in most events. The MJB is expected to be the dominant background component at larger values of $\Delta \phi(\mathbf{E}_T, \mathbf{p}_T)$. The dijet mass shape and normalization for the remaining MJB contribution in the sample is found by selecting events with $\Delta \phi(\mathbf{E}_T, \mathbf{p}_T) > 1.0$ and subtracting out the non-MJB backgrounds. The normalization is scaled up to account for the MJB contamination in the region $\Delta \phi(\mathbf{E}_T, \mathbf{p}_T) < 1.0$. The shape of the MJB is fit to an exponential in $M_{jj}$ to derive a dijet mass template. The MJB shapes of $M_{jj}$ and $\Delta \phi(\mathbf{E}_T, \mathbf{p}_T)$ distributions are verified with a large statistics MC sample.

The signal extraction is performed using a minimization of the unbinned extended negative log likelihood with the ROOFIT program [14]. Three $M_{jj}$ template distributions are used in the fit: the first is $V +$ jets and $t\bar{t}$-quark production [in the following referred to as “electroweak” (EWK) backgrounds] and is taken from Monte Carlo simulation; the second is the MJB template, where the slope and normalization are Gaussian constrained to their previously measured values; the third template describes the signal. The signal shape is comprised of the $WW$, $WZ$, and $ZZ$ distributions. This template is obtained from a Gaussian + polynomial fit to the signal Monte Carlo simulation where the mean and the width of the Gaussian distribution are linearly dependent on the jet energy scale (JES).

To assess the effect of systematic uncertainties on the measurement, we address separately two classes of sources: those that affect the signal extraction procedure and those that affect the signal acceptance in the cross section calculation. The signal extraction systematic uncertainties come from uncertainties in signal and background shapes. The shape uncertainties take into account the effect of jet energy resolution (JER), JES, MJB shape, and the shape of the EWK background. The jet energy scale and the shape and the normalization of MJB are treated as nuisance parameters in the fit and Gaussian constrained to their independently measured values. These uncertainties are therefore accounted for in the statistical uncertainty of the extraction.

The shape uncertainty for the EWK background is determined by using $\gamma +$ jets data [15] as an alternative background model in the $M_{jj}$ fit. All major non-MJB backgrounds include a gauge boson accompanied by jets. There are similarities between the $\gamma +$ jets and $V +$ jets production; however, due largely to the mass difference between the $\gamma$ and the $W/Z$, the kinematics is not identical. To take this into account, the $\gamma +$ jets data are weighted by the ratio of the dijet mass distributions of the EWK background MC samples to $\gamma +$ jets PYTHIA MC sample. We use these adjusted $\gamma +$ jets data to determine a systematic uncertainty on the EWK $M_{jj}$ template. Selection cuts applied to the $\gamma +$ jets events are not identical to those applied to the $E_T +$ jets sample. For example, the $Z$ decay into neutrinos will register as $E_T$ in the detector, while the photon $E_T$ will be measured in the calorimeter. For this reason, we cut on the vector sum of the photon $E_T$ and any $E_T$ present in $\gamma +$ jets events at 60 GeV, treating this sum as analogous to $E_T$ in $V +$ jets events. A further consideration in the construction of the $\gamma +$ jets template is the effect of $\gamma + V$ events, as these events will cause a peak in the $\gamma +$ jets dijet mass distribution. We subtract this contribution using the $\gamma + V$ PYTHIA sample. Finally, we perform two signal extraction fits using the default EWK and $\gamma +$ jets templates, respectively. The uncertainty due to the shape of the EWK background is then estimated as the difference in the results obtained from these two fits. The described method accounts for a combined effect of JES, JER, and modeling of jets in MC simulations on the EWK $M_{jj}$ template.

The uncertainty associated with the JES is the dominant source of systematic uncertainty on the acceptance and,
therefore, the cross section. Other less significant sources of systematic uncertainty that affect the measured cross section are jet energy resolution, initial and final state radiation (ISR/FSR), and parton distribution functions (PDF). A summary of all sources of systematic uncertainty is presented in Table I.

The measured yields for signal and backgrounds are given in Table II. Based on the MC simulation, the acceptances for the $WW$, $WZ$, and $ZZ$ production is 2.5%, 2.6%, and 2.9%, respectively. In the calculation of the combined diboson cross section, we assume that each signal process contributes proportionally to its predicted SM cross section: 11.7 pb for $WW$, 3.6 pb for $WZ$, and 1.5 pb for $ZZ$.

The number of signal events we extract corresponds to a cross section of 18.0 ± 2.8(stat) ± 1.1(lumi) pb, in agreement with the SM prediction of 16.8 ± 0.5 pb obtained using the MCFM V5.4 program [16] with CTEQ6.1M PDFs [17].

Figure 1 shows a comparison between the observed $\Delta \phi_{\not{E}_T}$ distribution and the MJB and EWK (signal + background) components. This distribution provides a strong consistency check on our MJB model. Figure 2 shows the fit result and a comparison between the expected signal and data after background subtraction. We bin the data as in Fig. 2 and obtain a $\chi^2$ of 9.4 for 9 degrees of freedom corresponding to a $p$ value of 40%.

In summary, we use the $\not{E}_T$ + jets final state to measure the $WW$ + $WZ$ + $ZZ$ cross section in $p\bar{p}$ collisions at

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<td>Jet energy scale, JES</td>
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<tr>
<td>Yield of EWK background events</td>
<td>36, 140 ± 1230</td>
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<tr>
<td>Yield of MJB events</td>
<td>7249 ± 1130</td>
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<td>Yield of diboson candidates</td>
<td>1516 ± 239</td>
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\( \sqrt{s} = 1.96\) TeV to be 18.0 \(\pm 2.8\) (stat) \(\pm 2.4\) (syst) \(\pm 1.1\) (lumi) pb. This is consistent with the SM prediction of 16.8 \(\pm 0.5\) pb. To assess the strength of the observed signal, the effects of parameter variations due to all relevant sources of uncertainty are studied by comparing the likelihood of the background-only fit with the full fit result, and converting the difference into significance numbers. We thus measure that the signal corresponds to a significance of at least 5.3 standard deviations from the background-only hypothesis. This is the first time the vector boson pair production has been observed in a hadronic final state at the Tevatron collider.

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